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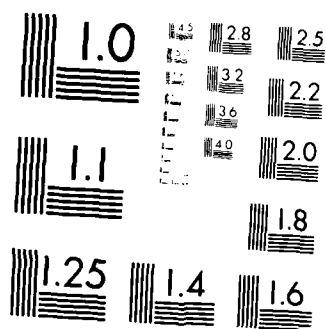
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MATTHEW J. KEPPER
Chief, Technical Information Division

INTEGRATION OF DETECTORS WITH
OPTICAL WAVEGUIDE STRUCTURES

Approved for public release;
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Prepared for the:

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This interim report summarizes progress made during the period 3/15/85-3/15/86 under the subject contract with most details appearing in publications referenced in this report. Major accomplishments occurred in the areas of (1) photodetectors formed on optical waveguide surfaces; (2) high-speed complementary metal-oxide-semiconductor electronic devices for signal processing and circuitry associated with these photodetectors; (3) improved techniques for laser recrystallization of silicon; (4) low loss optical waveguides; (5) theoretical analysis of low loss optical waveguides on silicon and gallium arsenide substrates; and (6) characterization of the materials utilized in the above devices by Raman spectroscopy with an inprobe.

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I. Summary (Abstract)

Integrated detection of light propagating in an optical waveguide with a photodetector array fabricated directly on the waveguide surface has been demonstrated. Devices having very good performance were formed by depositing polycrystalline silicon and laser recrystallizing it prior to device fabrication. Laser recrystallized silicon has also been evaluated for electronic device fabrication by forming complimentary metal-oxide-semiconductor transistors in this material and evaluating their electrical characteristics. Carrier mobilities, interface properties, leakage currents, and delay times have been measured. A Raman spectrometer with microprobe has been used to determine stress distributions in this material.

Low loss optical channel waveguides formed on silicon and gallium arsenide substrates are also being investigated. Thermal nitridation of silicon dioxide along with polycrystalline silicon masking is being used with a silicon substrate. Ion implantation of silicon and strip-loading with a silicon nitride strip are being investigated for formation of channel waveguides in gallium-aluminum arsenide multilayers on a gallium arsenide substrate. Optical waveguides on both silicon and gallium arsenide substrates are four-layer optical waveguides characterized by leaky modes. We have analyzed propagation of these modes and shown that a perturbation solution is valid except near mode cutoff.

II. Introduction

The present report describes the research progress during the period 3/15/85-3/15/86 for the contract AFOSR F49620-85-C-0044 entitled "Integration of Detectors With Optical Waveguide Structures." Most of the important results have been or will be published (See Section III for a list of Program publications) so the present report does not contain full detail of all accomplishments. For those wishing more detail in a certain area, specific publications will be referenced throughout this report. It is noteworthy that five journal papers, seven conference presentations with written proceedings, six conference presentations with no written proceedings, and two Ph.D. dissertations resulted from research either fully supported by or partially supported by this grant.

The primary effort in this contract has been the investigation of the fabrication of photodetectors having good performance directly on an optical waveguide surface. To do this, silicon is first deposited. Then, since the material onto which it is being deposited is not lattice-matched to silicon, a polycrystalline film of silicon results. However, single crystal silicon is required to form electronic devices having good performance. We thus recrystallize the polycrystalline silicon by local heating with scanning argon-ion laser light. In addition to laser heating we will soon be considering rapid thermal heating for recrystallization. During the period for which this report applies, significant progress has been made in recrystallizing silicon, fabricating photodetectors and complimentary metal-oxide-semiconductor (CMOS) devices in these recrystallized layers, and characterizing both

the quality of the materials and the quality of the devices by extensive electrical measurements and Raman spectroscopy. Progress has also been made in the area of low loss waveguides. This progress will be summarized in this report.

To support the overall goals of Air Force research, there has been significant interaction between personnel involved in the present and past AFOSR research program and those involved in military programs at the Air Force Avionics Laboratory, Rockwell International, McDonnell-Douglas, Battelle, Motorola, General Dynamics, Lockheed, Honeywell, and Oak Ridge National Laboratory. A number of papers have been co-authored by personnel from several of these institutions with personnel from the Solid State Electronics Laboratory at the University of Cincinnati.

The focal plane disector is a device structure which was originally conceived and first demonstrated by D. A. Ramey and J. T. Boyd of the University of Cincinnati working under AFOSR funding. This concept is now being contracted by the Air Force Wright Aeronautical Laboratories (Avionics Laboratory) to the Westinghouse Defense Electronics Center for development and use in optical signal processing systems.

III. Summary of Program Objectives

Research accomplishments at the University of Cincinnati made possible by previous AFOSR funding along with the expertise and laboratory facilities developed provide a sound basis for continued funding of the research now being carried out. Two major areas of research are being pursued with funding for one Ph.D. student in each area. The first area involves laser processing of semiconductors with emphasis on laser recrystallization of deposited silicon layers and photodetector and CMOS fabrication in these deposited layers. We have demonstrated that high quality photodetectors can be formed in these layers. We are now involved in demonstrating that the process can be carried out on integrated optical substrates such as LiNbO_3 , thus allowing integration of a quality photodetector array onto the same substrate as integrated optical devices such as the optical spectrum analyzer. As LiNbO_3 is sensitive to high temperatures and large electric fields, we plan to use the localized heating provided by the argon-ion laser along with an anti-transmission multilayer filter formed between LiNbO_3 and silicon.

The quality of the recrystallized layer is being examined by using Raman spectroscopy to evaluate spatial variations in strain and interface strain. A Raman spectrometer with microprobe attachment has been purchased for this research with funding from the DOD Instrumentation Program. Thorough electrical measurements of extensive CMOS test chip have been carried out, allowing an evaluation of the suitability of the laser recrystallized silicon for electronic device

fabrication. We are correlating electrical measurement with strain and the general quality of the recrystallized layers.

We have been performing several experiments directed primarily at improving the quality of laser recrystallized silicon. Specifically, we have investigated use of an argon-ion laser and a CO_2 laser simultaneously to perform recrystallization. We are currently beginning to investigate the use of rapid thermal heating (which uses flash lamps) to improve recrystallization.

The second major area of research involves SiO_2 optical waveguides formed on both gallium arsenide (GaAs) and silicon substrates. The emphasis here is on channel waveguides as compared to planar waveguides. For GaAs-based channel waveguides we are investigating using several novel techniques for channel confinement with the goal of achieving lower values of propagation loss than is normally achieved. For silicon-based channel waveguides, we are investigating using the waveguide fabrication process of thermal nitridation. We first showed that this process is applicable to fabrication of very low loss planar optical waveguides and we are trying to extend this technique to channel waveguide fabrication.

We plan to use our Raman spectrometer to analyze scattering from both waveguides formed in SiO_2 and those formed in GaAlAs. We expect that enhanced sensitivity should result from the extended path length associated with waveguide propagation. Raman scattering will also be used to probe for any structural changes associated with laser annealing of optical waveguides.

IV. Research Progress (3/15/85-3/15/86)

A. Photodetectors on Optical Waveguide Surfaces

We demonstrated early in this program integrated detection of light propagating in an optical waveguide by a photodetector array fabricated directly on the waveguide surface.^{1,2} The better performing devices were characterized by:

1. Low reverse pn junction leakage currents of the order of 10^{-12} A.
2. Reverse breakdown voltages of the order of 40-70 volts.
3. Photodetector dynamic ranges of 55-60 dB.

To achieve such good detector characteristics, the deposited silicon was first laser recrystallized. We used anti-reflection stripes to confine grain boundaries to regions between detectors.³ The silicon between detectors which included these grain boundaries was removed by plasma etching. In general, regions which were not laser recrystallized yielded poor characteristics, high reverse leakage currents, no voltage breakdown, and very weak optical response.

An area which we have studied recently concerns the question of detector characteristics for devices found at different locations on the wafer. In general, the uniformity was very good. Figure 1 shows a histogram of the variation in reverse leakage current at a voltage equal to one-half of the breakdown voltage for 206 different photodiodes located on the same wafer. From this histogram one readily sees the improved performance of photodiodes formed in regions which were laser recrystallized, as compared to those formed in regions which were not

REVERSE LEAKAGE CURRENT (AMPERES)



TOTAL PROBED DIODES: 206

FAILURE RATE: 10.1%

WORKING DIODES: 185 @d=5 um

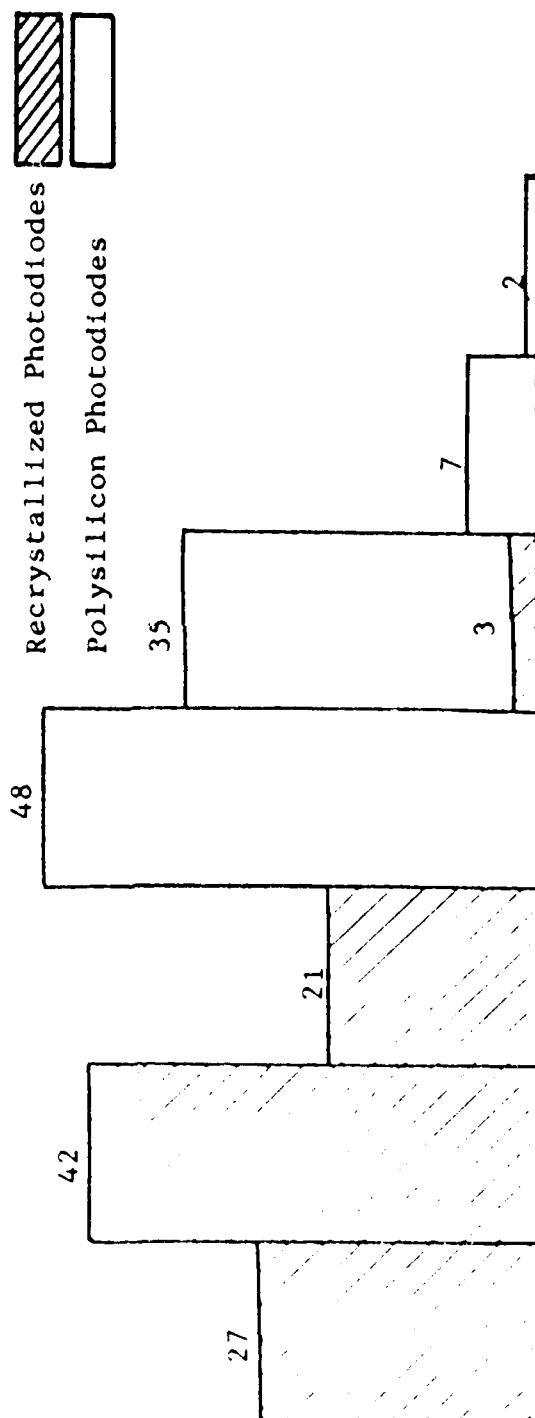


Figure 1 Histogram of p-i-n photodetector reverse leakage current measured at a voltage equal to one-half of the reverse breakdown voltage for 206 devices on the same wafer having an i region thickness of 5.0 microns.

laser recrystallized. We feel the variation in devices which were laser recrystallized could be improved by improving the stability of the laser deflection apparatus.

B. High Speed CMOS Devices Associated With Photodetectors

Previous studies of laser recrystallization of polycrystalline silicon on insulator have shown that different types of encapsulation layer structures can significantly affect the outcome of laser recrystallized films. Kamins compared the effect of stabilization layers on control of successful laser recrystallization,⁴ while Lasky compared the effect of a stabilization layer on surface roughness and laser power window.⁵ Le et al. showed that different encapsulation structures result in very different characteristics of the interface between the recrystallized film and the underlying insulation layer.⁶ Colinge et al. used anti-reflection nitride stripes to control the thermal profile in silicon during laser recrystallization so that the location of grain boundaries is selectively confined either to nonactive areas or to portions of devices that are not significantly affected by grain boundaries.^{1,7-9} Results of previous efforts suggest that different capping structures may be best suited for optimizing one particular property such as the range of usable laser powers, surface smoothness, or interface characteristics, respectively.⁴⁻⁶ However, a detailed study has not been made on the relative advantages and disadvantages among these capping layer structures.

We have made an extensive comparison of three different encapsulation structures by using Raman spectroscopy and metal-oxide-semiconductor (MOS) electrical test structures fabricated in these laser recrystallized films. The three encapsulation structures evaluated in this study are: (A) only 6 nm of silicon nitride, because it allows a large laser power window during recrystallization; (B) a more rigid layer composed of 64 nm of silicon nitride on top of 20 nm of silicon dioxide, for the smooth surface which results; and (C) 50 nm thick silicon nitride anti-reflection stripes with stripe widths of 6 microns and 16 micron center to center spacings, for the large single crystal grains which result.

Details of the laser recrystallization conditions and of the MOS test structure are presented elsewhere.¹⁰ Table I shows the summary of measured electronic device properties, while the distribution of electron mobilities is shown in Figure 2.

Wafers recrystallized with 6 nm of nitride (A-wafers) had a rough surface which may be the cause of the higher interface state density measured. Measurements of drain current in MOS transistors as a function of substrate bias, as shown in Fig. 3, indicate that A-wafers have much higher donor type interface traps between the recrystallized film and underlying insulator than B-wafers and C-wafers. Since the substrates worked as a gate for the channel at the bottom surface, the interface charge density estimated from the slope of the subthreshold current for A-wafer is $5 \times 10^{12} \text{ cm}^{-2}$. Good quality recrystallization of A-wafers is confirmed by the narrow Raman peak width, 3.4 cm^{-1} , and relatively good mobility when compared to C-wafers.

TABLE I
Summary of Device Properties
for Three Different
Capping Layer Structures

Device Properties	Capping Layer Structure		
	60 Å Si_3N_4 A-wafers	640 Å Si_3N_4 + 200 Å SiO_2 B-wafers	500 Å Si_3N_4 Stripes C-wafers
Electron Mobility ($\text{cm}^2/\text{volt-sec}$) /standard deviation	350 / 80	270 / 90	400 / 60
Hole Mobility ($\text{cm}^2/\text{volt-sec}$) /standard deviation	180 / 50	150 / 40	200 / 40
Threshold Voltage (volts) (n channel) /standard deviation	1.5 / 0.2	1.9 / 0.2	1.5 / 0.2
Fixed Oxide Charge Density (cm^{-2})	2×10^{11}	1×10^{11}	2×10^{11}
Interface Trap Density (cm^{-2})	6×10^{10}	4×10^{10}	NA
Leakage Current/micron (A) ($V_{ds} = V_{gs} = V_{sub} = 0.0 \text{ V}$)	1×10^{-9}	1×10^{-12}	1×10^{-12}
Minority Carrier Generation Time (ns)	2	2	NA
Ring Oscillator Delay Time Per Stage (ns)/ $L_{eff}(\mu\text{m})$ ($V_{dd} = 10.0 \text{ V}$)	3.7 / 5.9	4.3 / 6.3	4.5 / 8.3
Stress ($\times 10^9 \text{ dyn/cm}$) /standard deviation	7.8 / 0.9	7.3 / 0.4	6.7 / 0.7
Raman Peak Half-width (cm^{-1}) /standard deviation	3.4 / 0.1	4.1 / 0.1	3.3 / 0.3
Usable Laser Power Window (Watts)	2	0.5	.75

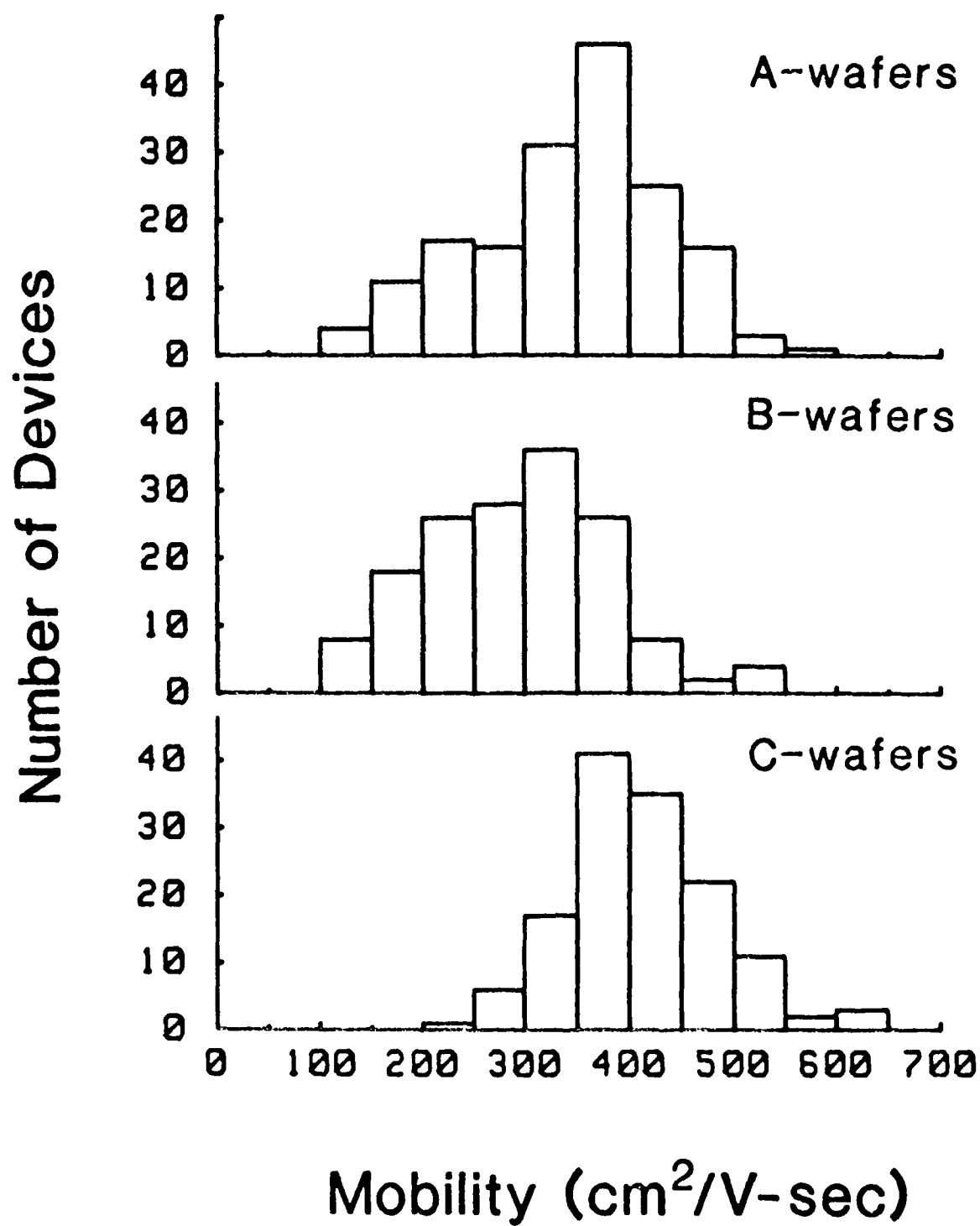
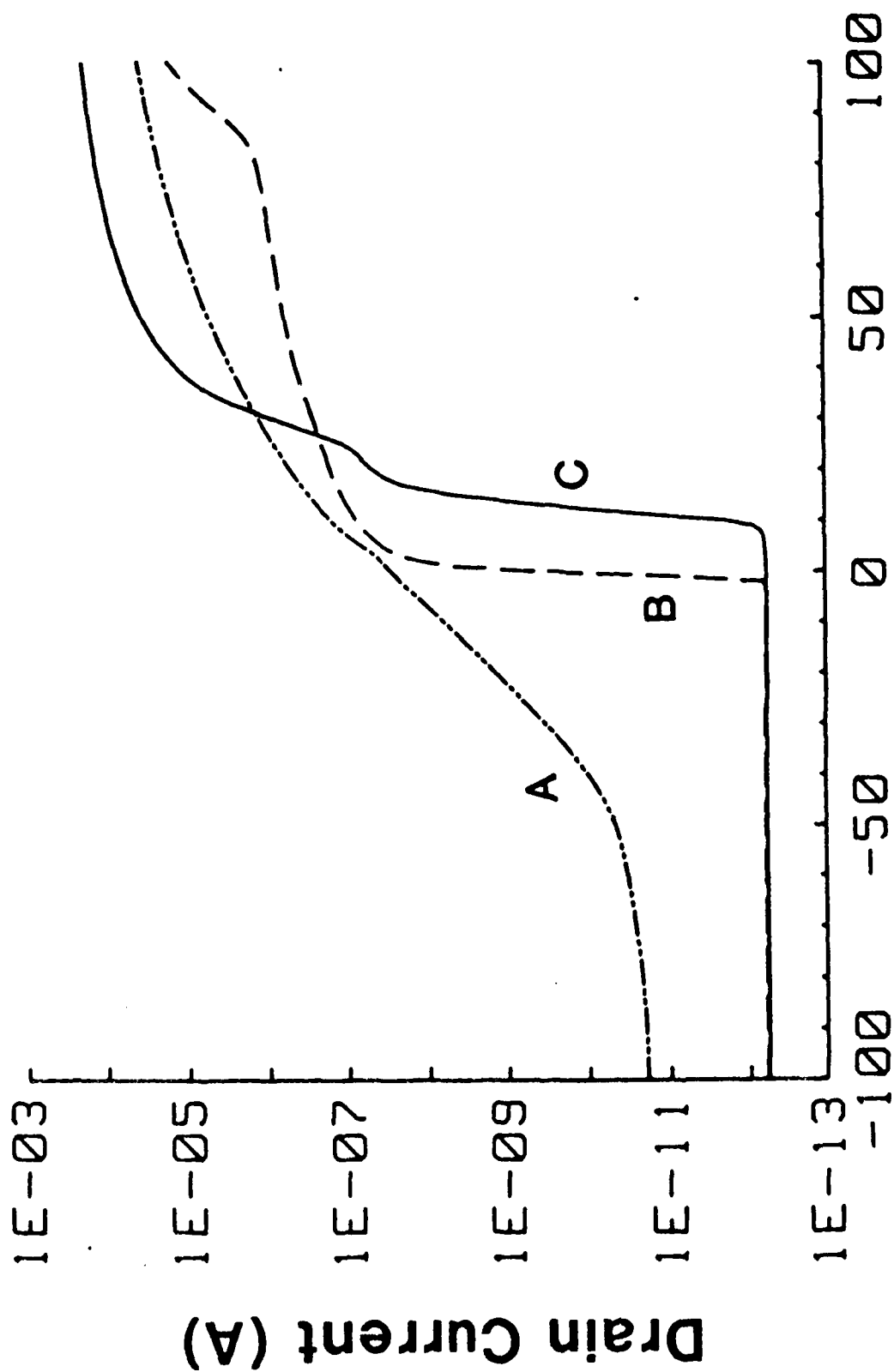


Figure 2. Number of devices having various values of mobility for three different encapsulation structures described on page 9.



Substrate Bias (V)

Figure 3. Drain leakage current as a function of substrate bias for n-channel MOS transistors having $W/L = 250$ microns/8 microns. Curves A, B, and C correspond to the three different encapsulation structures described on page 9.

Wafers with 64 nm nitride on top of 20 nm oxide capping structure (B-wafers) were characterized by a very smooth surface after recrystallization. The interface state density was lower than that of A-wafers while the fixed oxide charge was the lowest among the three types of wafers tested. Grain sizes in B-wafers were similar to those in the A-wafers, on the order of 50 square microns. The sensitivity to laser power associated with B-wafers, however, required critical adjustment of the laser power for each wafer to obtain good recrystallization. Nevertheless, 2 out of 10 wafers still failed to be recrystallized properly. The lower mobility and width of the Raman peak, 4.1 cm^{-1} compared to 3.4 cm^{-1} for A-wafers and 3.3 cm^{-1} for C-wafers, indicate that the distribution of stress is not as uniform as for the other two sets of wafers.

Wafers with 50 nm antireflecting stripes (C-wafers) were characterized by the best crystallinity and the most consistent carrier mobilities measured. Good control of laser power for this case is important to successful recrystallization. Unlike the random grain boundaries observed in the other two sets of wafers, these wafers have a distinct pattern of grain boundaries with a long grain boundary under the stripe location with nearly perpendicular branches that penetrate 4-5 microns into regions between the stripes. Distances between these branches range from a few microns to several hundred microns. The grain boundaries in A-wafers and B-wafers do not significantly affect the operation of the transistors since usual values of gate voltage are large enough to overcome the energy barrier associated with these grain

boundaries.¹¹ We suspect, however, that the energy barrier associated with the long grain boundaries under the stripe locations are much higher than those associated with random grain boundaries since all transistors having channel lengths of 16 microns (the distance between stripes) failed to operate, whereas those with shorter channel lengths operated successfully. The poor surface topology and possible high energy barrier indicate that if device geometries larger than the separation between stripes in both planar directions are required, a different capping layer such as 6 nm of nitride is needed to cover those regions.

C. Improved Recrystallization Techniques

Laser recrystallization of polycrystalline silicon deposited on an insulating substrate has been carried out using two lasers operating at 514.5 nm (Ar^+) and at 10.6 microns (CO_2) respectively. The use of two lasers allows somewhat independent spatial control of the temperature in the polysilicon layer and in the insulating oxide layer below it. Preliminary work suggests that this technique enables us to achieve improvement in the quality of the recrystallized layer over recrystallization done with only the Ar^+ laser. Optical micrographs show that this method increases melt widths by at least a factor of three over recrystallization with the Ar^+ laser only. Grain sizes a factor of at least two wider than those obtained from similar recrystallization experiments performed with only the Ar^+ laser have been observed.

A second approach to improved recrystallization is beginning to be investigated. This technique uses rapid thermal heating (from flash lamps) for local heating. The advantage of using this technique is that the entire wafer can be heated at the same time. We expect that the role of anti-reflection stripes should be useful in localizing grain boundaries to beneath the stripes, even though a broader range of wavelengths is emitted from the flash lamps than from the Argon ion laser operating on many lines.

D. Low Loss Optical Waveguides

Research directed towards achieving ultra-low loss optical channel waveguides on Si and GaAs substrates is being carried out. For silicon substrates thermal nitridation of SiO_2 using rapid thermal heating combined with either local oxidation or masked nitridation is being explored for formation of low loss channel waveguides. This research builds on results in which planar waveguides formed by thermal nitridation have been demonstrated with losses as low as 0.06 dB/cm.

To form low loss channel optical waveguides on GaAs substrates, we begin with a GaAlAs layer having a low percentage aluminum concentration deposited onto a similar layer, but one having a higher aluminum concentration; both layers being deposited onto a GaAs substrate. This structure forms a planar waveguide. Lateral confinement achieved by depositing a thin Si_3N_4 dielectric strip onto the surface of the planar guide or by ion implanting Si or S into the guiding layer outside the desired channel region is being investigated.

E. Optical Waveguide Theoretical Analysis

We have analyzed some properties of optical waveguide propagation in a specific class of four-layer planar structures for situations in which the properties of the layers constrain mode solutions to be close to cutoff. The specific class of four-layer structures is applicable to many waveguides formed on silicon and gallium arsenide substrates. In these four-layer structures the upper layer is a low refractive index layer corresponding to air or a very thick covering. The second layer corresponds to the guiding layer and has a refractive index larger than that associated with the first and third layers. The third layer is a cladding layer which has the role of isolating light in the guiding layer (layer 2) from the fourth layer, which is very thick, has a higher refractive index than the other layers, and is strongly absorbing at the wavelength of interest. Four-layer structures such as this can be used to model the variety of low-loss planar optical waveguides formed on silicon substrates with a silicon dioxide cladding layer and to model $\text{Ga}_{1-x}\text{Al}_x\text{As}$ planar waveguides grown on a GaAs substrate with an intervening $\text{Ga}_{1-y}\text{Al}_y\text{As}$ cladding layer ($y > x$).

Since one of the outer semi-infinite layers in the four-layer structure being considered here has a larger refractive index than the other layers, the waveguide modes are not strictly bound modes but instead leaky modes. The modes are thus characterized by a complex propagation constant with the imaginary part corresponding to attenuation due to energy radiating away from the guiding layer. For a

wide range of refractive indices and layer thicknesses, however, this attenuation can be quite small so that light can propagate over distances long compared to the size of typical substrates with negligible attenuation. For this range of parameters, the solution of the boundary value problem yields a propagation constant which is accurately approximated by the corresponding solution for the first three layers; that is, by omitting the fourth or substrate layer and assuming the third or cladding layer is semi-infinite. The propagation constant for this three-layer situation is real, corresponding to a bound mode. Our purpose is to consider mode propagation properties for ranges of parameters which yield propagation constants between these values and cutoff and, in particular, to present numerical results for the region close to cutoff for the two examples discussed above.

F. Raman Microprobe Characterization

A Raman spectrometer with microprobe having 1.0 micron spatial resolution has been used to characterize some physical properties of the recrystallized silicon films. Stress in silicon films is directly proportional to the shift of the longitudinal optical phonon frequency compared with the nearly stress-free single crystal silicon value measured from the Raman spectrum. The half-width associated with this peak in the Raman spectrum may be related to inhomogeneities in the stress distribution in crystalline silicon or, in the case of polysilicon, to the size of the crystallites or to the degree of

crystalline order. The measured half-widths for bulk single crystal Si and for the polysilicon as deposited were 3.1 cm^{-1} and 9.2 cm^{-1} , respectively. We have also used the Raman system with microprobe to evaluate the mole fraction of Al in GaAlAs layers.

V. List of Program Publications

Journal Papers

H.E. Lu, J.T. Boyd, H.E. Jackson, and J.L. Janning, "Characterization of the Effects of Different Capping Layer Structures on the Laser Recrystallization of Silicon by Using Electrical Test Structures and Raman Spectroscopy," to be published.

A. Naumaan and J.T. Boyd, "Ring Resonator Fabricated in Phosphosilicate Glass Films Deposited by Chemical Vapor Deposition," IEEE/OSA Journal of Lightwave Technology, accepted for publication.

D.E. Zelmon, J.T. Boyd, and H.E. Jackson, "Low Loss Optical Waveguides Fabricated by Thermal Nitridation," Applied Physics Letters, Vol. 47, pp. 353-355, 1985.

J.T. Boyd, R.W. Wu, D.E. Zelmon, A. Naumaan, H.A. Timlin, and H.E. Jackson, "Guided Wave Optical Structures Utilizing Silicon," Optical Engineering, Special Issue on Integrated Optical Circuit Engineering, Vol. 24, pp. 230-234, 1985.

R.W. Wu, J.T. Boyd, H.A. Timlin, Howard E. Jackson, and John L. Janning, "Optical Waveguide Detection: Photodetector Array Formed on the Waveguide Utilizing Laser Recrystallized Silicon," Applied Physics Letters, Vol. 24, pp. 391-395, 1985.

Conference Presentations with Written Proceedings

D.E. Zelmon, W.C. Borland, C.J. Hsieh, H.E. Jackson, and J.T. Boyd, "Near Cutoff Propagation in Low Loss Optical Waveguides Formed on SiO₂/Si Substrates," to be presented at and published in the Proceedings of the SPIE International Conference on Integrated Optical Circuit Engineering IV, Cambridge, MA, September, 1986.

H.E. Jackson, S. Dasgupta, H.E. Lu, T.D. Mantei, and J.T. Boyd, "Raman and Brillouin Scattering from Deposited Semiconductor Layers," to be presented at and published in the Proceedings of the SPIE Symposium on Optoelectronics, Cambridge, MA, September, 1986.

H.E. Lu, J.T. Boyd, and R.W. Wu, "A CMOS Test Structure to Evaluate Laser Recrystallized Silicon-On-Insulator," presented at and published in The Proceedings of the IEEE VLSI Workshop On Test Structures, Long Beach, CA, February, 1986.

S. Dasgupta, H.E. Jackson, and J.T. Boyd, "Two Beam Laser Recrystallization of Silicon On An Insulating Substrate," presented at and published in The Proceedings of the Materials Research Society Meeting, Boston, December, 1985.

D.E. Zelmon, H.E. Jackson, and J.T. Boyd, "Use of Thermal Nitridation to Fabricate Low Loss Planar Optical Waveguides in SiO₂," presented at and published in the Proceedings of the Second SPIE International Conference on Integrated Optical Circuit Engineering, Cambridge, MA, September, 1985.

J.T. Boyd, H.E. Jackson, D.E. Zelmon, and R.W. Wu, "Low Loss SiO₂ Optical Waveguides Formed By Thermal Nitridation and Photodetectors Formed on Waveguide Surfaces Utilizing Laser Recrystallized Silicon," presented at and published in The Proceedings of the 1985 National Science Foundation Grantee-Users Meeting on Optical Communications, Cornell University, June, 1985.

H.E. Jackson and J.T. Boyd, "Low Loss Thin Film Materials For Integrated Optics," presented at and published in The Proceedings of The American Physical Society Topical Meeting on Basic Properties of Optical Materials, May, 1985.

Conference Presentations Without Written Proceedings

S. Dasgupta, H.E. Jackson, and J.T. Boyd, "Laser Recrystallization of Polysilicon by Simultaneous Use of Ar⁺ and CO₂ Lasers," presented at the American Physical Society Meeting, March, 1986.

D.E. Zelmon, J.T. Boyd, and H.E. Jackson, "Low Loss Planar Optical Waveguides Fabricated on Silicon," presented at the Midwest Symposium on Circuits and Systems, Louisville, Kentucky, August, 1985.

H.E. Lu, R.W. Wu, J.T. Boyd, and J.L. Janning, "A CMOS Test Circuit Formed on Laser Recrystallized Silicon - On - Insulator," presented at the Joint Spring Meeting of the Ohio section of the American Physical Society and the Southern Ohio Section of the American Association of Physics Teachers, University of Cincinnati, Cincinnati, Ohio, April 12-13, 1985.

S. Dasgupta, H.E. Jackson, and J.T. Boyd, "Laser Recrystallization of Si on SiO₂ By Ar⁺ and CO₂ Laser Irradiation," presented at the Joint Spring Meeting of the Ohio Section of the American Physical Society and the Southern Ohio Section of the American Association of Physics Teachers, University of Cincinnati, Cincinnati, Ohio, April 12-13, 1985.

J.T. Boyd, "Fabrication of Electronic Devices Using Laser Recrystallized Silicon," presented at the Tri-State Symposium on Laser Applications, Cincinnati, April, 1985.

S. Dasgupta, H.E. Jackson, and J.T. Boyd, "Two Beam Laser Recrystallization of Silicon on an Insulating Substrate," presented at The American Physical Society Meeting, March, 1985.

Ph.D. Dissertations

D.E. Zelmon, "Planar Optical Waveguides Fabricated in Thick Thermally Grown Silicon Dioxide Films," Ph.D. Dissertation, University of Cincinnati, 1986.

A. Naumann, "Phosphosilicate Glass For Integrated Optics," Ph.D. Dissertation, University of Cincinnati, 1985.

VI. Professional Personnel

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William C. Boreland

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VII. Acknowledgements

The author wishes to acknowledge contribution from several others not listed as authors, but who contributed to the research described herein. In particular, Professor Howard E. Jackson participated significantly in all aspects of the research. The graduate students listed on the previous page also participated in research described in this report. The technical assistance of James T. Garrett and Roger A. Kirschner in performing a variety of specialized tasks is appreciated.

VIII. References

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